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Rainwater harvesting as an alternative to potable water use for urban landscape irrigation: A case study

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ABSTRACT

Climate change and recurrent droughts are increasing pressure on freshwater resources in Bulgaria, where potable water is still commonly used for urban landscape irrigation. This study evaluates alternative irrigation water supply strategies for two central parks in Gabrovo (a region with periodical water shortages) by combining rooftop rainwater harvesting (RWH) with alternative local sources. Irrigation demand was quantified from metered consumption (2020–2023), while RWH potential was assessed using long-term precipitation records and roof areas of the city's central Library (600 m²) and Drama Theatre (650 m²). With a runoff coefficient of 0.9, harvested rainwater can cover at most about 29% of seasonal irrigation needs, indicating that standalone RWH is insufficient. Three hybrid options were therefore designed and compared via discounted life-cycle cost analysis over 30- and 50-year horizons, with varying discount rates (0, 4, 8%) and technological equipment replacement intervals (10, 15, 20 years): (1) RWH with potable network backup (RW+N); (2) RWH with supplementary intake from a drainage well in the Sinkevitsa riverbed (RW+W); and (3) RWH with supply from the nearby Sinkevitsa dam via a rehabilitated pipeline (RW+D). At realistic discount rates (4%), RW+W yields the lowest present value costs, fully eliminates potable water use, and offers robust drought resilience with manageable technical complexity, whereas RW+D is consistently the most expensive and operationally risky option. Furthermore, the parametric analysis highlights strong interactions among DR, analysis horizon and TER. At low DRs, shorter TERs significantly increase PV because multiple replacement cycles are only weakly discounted. At high discount rates, the influence of TER diminishes and OPEX-intensive configurations and RW+N can become comparatively more attractive. Beyond the local context, the proposed methodology can inform climate adaptation strategies in other European municipalities facing similar environmental and socio-economic challenges.

Keywords: rainwater, rainwater harvesting, rainwater use, urban landscaping, feasibility study, case study.

INTRODUCTION

The global risk of freshwater scarcity is rapidly growing. Factors like climate change, population growth, and rising demand for clean water from agriculture and cities are amplifying its projection to society [Damania et al., 2025]. According to the International Panel on Climate Change (IPCC) report from 2022 and the UN World Water Development Report 2024, it is estimated that approximately 2.2 billion people are deficient in safe drinking water, and 4.2 billion people do not have access to sanitation [IPCC, 2022; UN, 2024]. Also, concerning the Sustainable Development Goals (SDG) of the United Nations (UN), and particularly SDG 6 (achieving clean water and sanitation for all by 2030) – none of the priority targets for the goal are currently on the desired track [UN, 2024]. Concurrently, the heat rise and the recent hydrologic extremes leave several billion people without adequate water access for at least one month each year. In this context, major scientific reviews and global reports from recent years warn that droughts and low-flow conditions will become more frequent and persistent in many regions, increasing water-related risks to economies and ecosystems [Hagenlocher et al. 2023; Rahman et al., 2025; OECD, 2025].

The European Union (EU) is currently estimating the risks and is working towards confronting recurrent water stress. According to the reported data from the European Environment Agency (EEA), water scarcity affected about 34% of the EU's territory during at least one season in 2022 [EEA, 2025]. Furthermore, no significant reduction in the affected area since 2010 was detected despite the declining rate of abstractions. Wider ecosystem impacts from drought remained above the 2000–2020 average in 2023, underscoring the need for structural adaptation [EEA, 2024]. Southeastern Europe (including Bulgaria) has faced particularly severe low-flow risks and multi-year deficits after the extreme 2022 event. In Bulgaria, national institutions recognize increasing drought frequency and reduced runoff under climate change, and water supply restrictions (such as regional water regimens) have periodically been imposed during dry spells [IPCC, 2022]. A significant reason for the local water shortages is the use of potable water from the water supply system for irrigation purposes in the country.

Against this backdrop, rainwater harvesting (RWH) and water reclamation are practical measures to buffer irrigation demand during drought periods, reduce reliance on potable supplies, and lower operating energy per unit of non-potable water [Tsanov et al., 2023; Tsanov et al., 2024]. In the literature RWH is considered a cost-effective adaptation strategy that can support urban irrigation and reduce competition for drinking water [Crosson et al., 2021]. In Europe, the policy environment increasingly supports alternative water sources. Some of the main documents that focus on the subject are the EU Water Framework Directive (WFD) that sets the overarching objective of good status and integrated water management, the EU Adaptation Strategy that calls for strengthening drought preparedness and water resilience, and Regulation (EU) 2020/741 that establishes minimum requirements for safe water reuse, particularly relevant where reclaimed water substitutes for freshwater in irrigation [Directive 2000/60/EC; EC, 2021; Regulation (EU) 2020/741]. Additionally, design and operation of on-site RWH systems for non-potable uses, including irrigation, are addressed by the European standard EN 16941-1:2018, providing technical guidance on sizing, installation, and maintenance [EN 16941-1:2018].

On a local level, in Bulgaria, some regions are more prone to droughts than others. Throughout the years Gabrovo city and the region around it have occasionally experienced water shortages. Over the past decade, several municipalities in the Gabrovo region, most notably Sevlievo, Dryanovo, Tryavna, and individual villages within Gabrovo municipality, have repeatedly experienced water supply restrictions due to prolonged droughts and limited resource availability. These measures, ranging from reduced pressure and scheduled supply interruptions to complete bans on non-potable uses, highlight the persistent vulnerability of the area's water management system to seasonal and climatic stressors [https://gabrovo.bg/; https://zagabrovo.bg/; https://zaistinata.com/; https://www.dnevnik.bg]. These events are most evident during the summer months, when the need for irrigation increases – both on private properties and in municipal green areas, parks, etc., since Gabrovo uses mainly drinking water from the public water supply network for watering purposes.

The objective of this study is to address the issue of water scarcity in the area of Gabrovo by investigating the potential of RWH and alternative water sources for the irrigation of two major urban green zones in its city center. Currently, rainwater is discharged directly into the municipal sewerage system, while available alternative sources remain unexploited. This research further evaluates the potential for reducing, or entirely eliminating, the use of potable water for irrigation purposes through a comparative feasibility assessment of the most appropriate options for the case study. The results are expected to provide valuable empirical evidence to support future research on RWH systems, contribute to the scientific literature with practical insights, and enhance methodological approaches for the sustainable management of urban water resources.

MATERIALS AND METHODS

Description of the site

Gabrovo region

The town of Gabrovo is located in central northern Bulgaria, and it is the longest town in the country (25 km) [https://roundtripbulgaria.com/]. It is situated along the Yantra River in the northern part of the Balkan Mountains. According to the latest census data from the National Statistical Institute (NSI), the population of Gabrovo is 45

940 people [NSI, 2021]. The map of Gabrovo city is presented in Figure 1.

The region has a diverse semi-mountainous and mountainous topography. The climate is temperate continental, with cold winters and relatively warm summers. The region is characterized by high annual sunshine duration. Average annual temperatures are around 10.5 °C [World Bank Portal, 2025]. Precipitation has a continental character with average annual rainfall of around 900 L/m² [World Bank Portal, 2025]. In the high mountains, snow cover lasts about 110 days.

Park area and current irrigation systems

The target area for the analysis in the study is located in the city center of Gabrovo, and its general location is presented in Figure 1. It is adjacent to the Yantra river. The total green area is divided into two park zones (Zone 1 and Zone 2) by the Yantra river's tributary – Sinkevitsa river. A more detailed outlook of the two zones with their specific elements is presented in the geodetic survey drawings in the options analysis section in Figure 5 to Figure 7. Both park zones feature lawns, trees, walkways, and other amenities such as fountains, monuments, and an artificial lake. The average altitude of the area is 390 m.

The irrigation season covers the period from April-May to October-November and may be extended or shortened depending on the specific weather conditions throughout year. Irrigation is carried out on a daily basis during the dark part of the day. The duration of each irrigation cycle is manually controlled through time-based timers, and no records of the seasonal settings are kept. It is also unknown how frequently the system is re-adjusted during the irrigation season. The length of each irrigation event is determined according to prevailing meteorological conditions, primarily daytime and nighttime temperatures. During cooler months, the frequency and duration of irrigation cycles are reduced.

The two park zones have separate irrigation systems, which were both built about 15 years ago, and are currently in good operational condition. The gross area covered by the system is approximately 8700 m² for Zone 1 and 3000 m² for Zone 2. It is designed and implemented as a stationary sprinkler system with automated water distribution. Both systems are automated, and the irrigation volume is adjusted by the irrigation time. Each irrigation system consists of an underground network of polyethylene pipes and above-ground sprinklers, divided into several independent control circuits. The water supply to the sprinklers is controlled by electromagnetic valves. When the valves are opened, under the pressure of the water, the sprinklers automatically rise above the ground to a height of 10–30 cm and retract when the solenoid valve stops the water supply and the pressure in the system drops. The pressure required for normal operation of the system is 25 m. Over the years, partial repairs have been carried out to replace or relocate sprinklers, programmers, etc.

Both park zones are supplied with water from the city's public water supply network. Each zone has its own separate water meter shaft for the measurement of their water consumption since

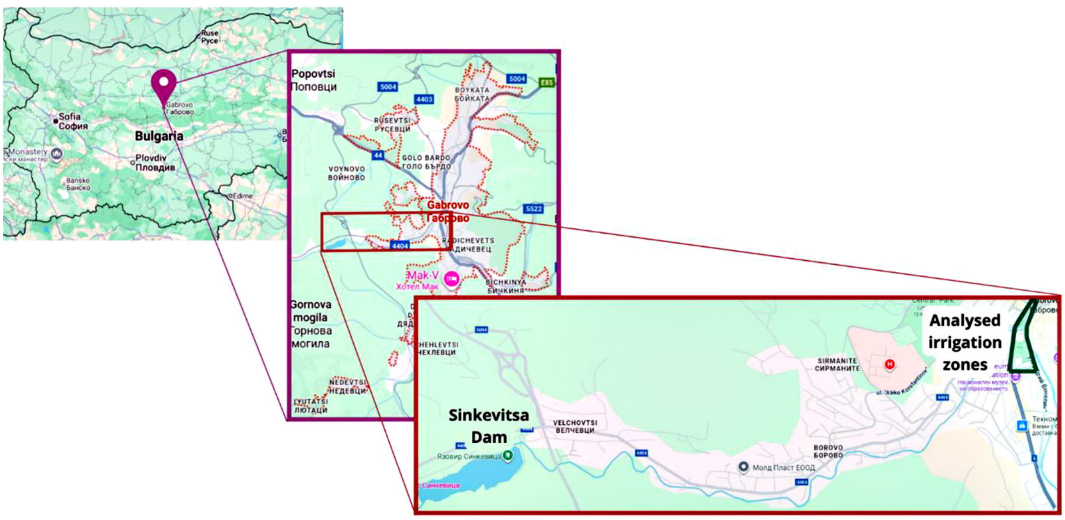

Figure 1. Map of Gabrovo city, Sinkevitsa dam and the analyzed zones for irrigation

the municipality is taxed at the current water prices. The connection from the public water supply system to each zone is through a D=63 mm polyethylene (PE) pipe that is connected to the public pipe D=400 mm PE. Throughout the entire park area, neither stormwater from the alleys nor rainwater collected from the roofs of adjacent buildings is retained, infiltrated, or reused. Roof runoff is captured by gutters and downspouts and discharged directly onto the surrounding ground surface, while runoff from the alleys is conveyed through stormwater inlets and drained into the municipal sewer system.

Current irrigation needs

The water consumption for the irrigation of the two zones over the period from 2020 to 2023 is based on the data from the local Water Operator. The volumes are summarized in Table 1.

The average annual water volume for the reviewed time period for Zone 1 is 1418 m^3, and for Zone 2 – 238 m^3.

Potential water sources for irrigation

Rainwater harvesting (RWH) potential – target roofs and equalization tank locations

- Rainfall data

To assess the collected volumes from a potential rainwater harvesting system, precipitation data for the respective months was required. For this purpose, data from the monthly bulletins of the National Institute of Meteorology and Hydrology in Bulgaria (NIMH) for the years 2007 to 2023 were used to determine the average monthly precipitation values. Since the bulletins do not provide information from the rain gauge station in Gabrovo, the nearest station with similar characteristics was used – that of Veliko Tarnovo. The rainfall (precipitation) and temperature data from the Veliko Tarnovo station are presented in Figure 2.

- Target roofs and equalization tank locations

The two most suitable sites that were identified for RWH in the area are the roofs of the Library and the Drama Theater buildings. Located close by, they have large roof areas, and minimal water treatment will be required because the water will be collected directly from the roofs rather than from the ground. Also, the Library and the Theater are adjacent to buildings that are no longer in use and can be used for placement of equalization tanks for the temporary storage of the collected rainwater before the irrigation event occurs. The options for the exact placing of the tanks have been studied in detail, and two possible locations have been identified – the decommissioned "Ossuary" next to the City's Library building and the inactive public restroom near the Drama Theater.

The Library building is located in Zone 1, while the Drama Theater is adjacent to Zone 2. The roofs are sloped with external and internal drainpipes (Figure 2). The major parts of both roofs are drained along the external facade and the water from them is suitable for relatively easy collection and subsequent use. The minor part of the roofs is drained internally and connected to the building's sewer system. Collecting rainwater from the internal downspouts would be an expensive and complicated solution, as an additional rainwater drainage system would have to be built through the building and the existing system should be reconstructed. For those reasons only

Table 1. Water consumption for irrigation for both green zones [data source: the Water Operator - Gabrovo Water Supply and Sewerage Ltd.]

Total m^3 consumption for irrigation					Average water use per month for both zones
Month/Year	2020	2021	2022	2023	
5	270	2	101	0	93
6	180	79	211	0	118
7	355	270	268	53	237
8	547	131	238	194	278
9	483	426	508	394	453
10	313	501	343	315	368
11	2	243	129	65	110
Total	2150	1652	1798	1021	1655

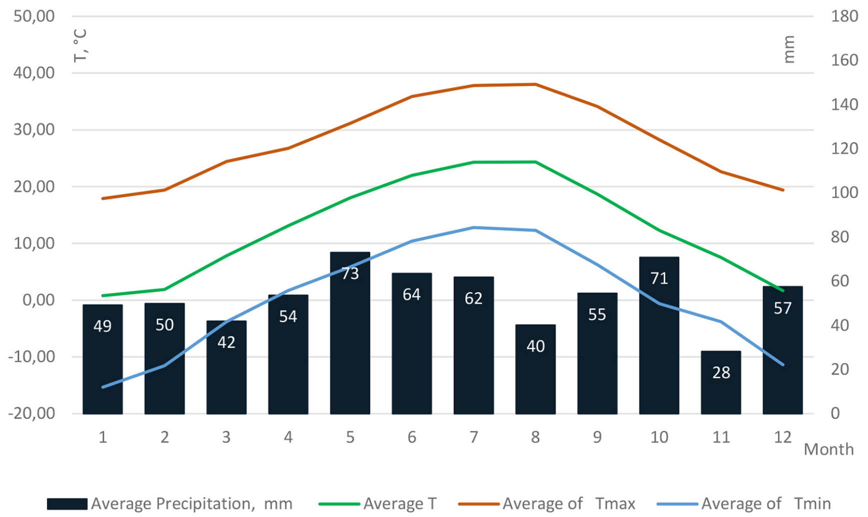

Figure 2. Yearly rainfall data from the closest rain gauge (Veliko Tarnovo) [data source: NIMH]

the external drainpipes with their respective roof areas were included in the analysis for potential RWH. The total area that is available for RWH through the external facade is approx. 600 m^2 for the Library and 650 m^2 for the Drama Theater.

Additional alternative water sources

- Gabrovo public water supply system

Currently, water for irrigation is supplied by the public water supply system of the city of Gabrovo. The water is with drinking water quality and no alternative water sources are used in order to save it. The water reservoir that supplies the area where both irrigation zones are located is at an elevation of 457.50 m. This provides a head of approximately 40 to 50 m at the inlet of the irrigation systems.

- Sinkevitsa Dam

According to the data, provided by Gabrovo Municipality, the dam was built for flood protection and for the use of its water by the former Kartalov factory. The factory is currently out of operation. There are a few smaller legal entities on its site that do not use water from the dam but are connected to the city's water supply network. The dam has been privately owned by the municipality since 1997 but the steel water pipeline from the dam to the factory with a diameter of 219 mm and a length of 3000 m is neither operational, nor does the municipality own it. However, procedures for acquiring ownership by the municipality are initiated. Even though the possession of the property is not yet established, the possibility of using water for irrigation from the Sinkevitsa dam is considered in the current study.

- Sinkevitsa River

Sinkevitsa river is a tributary of the most substantial local river – Yantra river. It is registered with a number BGIYN900R1015 in the Danube Region Basin Directorate in Bulgaria [MOEW, 2024]. The river is partially corrected and fed by the Sinkevitsa dam spillway and overflow. Sinkevitsa river was selected instead of the larger river – Yantra, since the latter is listed as an ecologically protected water body by national law and the administrative procedures for allocating water from its bed would be much more complicated.

Development of the alternative options

Based on the data from the previous subsections, an option analysis for the possible irrigation water sources was prepared. The options were first valued and after that a discounted LCCA and sensitivity analysis were performed in order to estimate the optimal solution for the case study. The methodology for the evaluation and the analysis is described in the following subsections.

Valuation of the options

The costs for the options cover the costs of construction, installation and commissioning works, technological equipment (including delivery and installation), electrical energy use, and expenditures for drinking water use to the Water Operator of Gabrovo (for the options that uses it). The prices of the technological equipment are based on current offers from supplier and representative companies, while the construction, installation and commissioning works pricing is based on the current market prices in Bulgaria.

Discounted life-cycle cost analysis (LCCA)

The alternatives were evaluated using a discounted life-cycle cost analysis (LCCA). This approach allows all capital and operational expenditures (CAPEX and OPEX) to be assessed within a unified economic framework by discounting future costs to their PV. The method is widely recognized in engineering practice and enables an objective comparison of alternatives with different cost structures and lifespans. By applying LCCA, the option with the lowest present value of total costs can be reliably identified as the most economically advantageous solution. The reliability of life cycle cost (LCC) assessments depends strongly on several methodological parameters that influence how future costs are represented. As demonstrated in Pernetti et al. 2021, the analysis horizon, the assumed technological equipment replacement cycle (TER), and the selected discount rate (DR) are among the most influential drivers of variability in LCC results [Pernetti et al., 2021]. Differences in these parameters can substantially shift long-term cost projections and may alter the comparative performance of alternative solutions. For this reason, it is essential to examine multiple combinations of time horizons, replacement periods, and discount factors to ensure a robust and well-grounded option analysis.

All solutions considered in the option analysis were evaluated over two time horizons: 30 years and 50 years of system operation. In addition, each option was assessed under three possible technological equipment replacement (TER) intervals – 10, 15, and 20 years. Each sub-option was analyzed using discount rates of 0%, 4%, and 8% for the present-value (PV) calculations. All analyses were carried out in the official European currency, the euro (EUR). The main economic parameters used in the analysis are shown in Table 2.

The PV of future costs was calculated using discrete annual cash flows and a net present value (NPV) formulation [Kneifel and Webb, 2020]. Year-by-year costs, including operational expenditures and scheduled equipment replacements, were explicitly modelled and discounted according to:

$$PV = \sum_{t=1}^{n} \frac{C_t}{(1+d)^t} \tag{1}$$

where: C_t denotes the total cost incurred in year t, d is the discount rate, and n is the analysis period. Initial investment costs were accounted for in year zero, while the residual value was calculated proportionally to the remaining service life of the equipment at the end of the analysis horizon and discounted accordingly [Kneifel and Webb, 2020].

The residual value of the technological equipment at the end of the analysis period was calculated based on the remaining service life, assuming linear depreciation, according to:

$$RV = C_{\text{inv}} \cdot \frac{L_{\text{rem}}}{L_{\text{tot}}} \tag{2}$$

where: RV is the residual value at the end of the analysis period, C_{inv} is the initial investment cost of the equipment, L_{tot} is the total assumed service life of the equipment, and L_{rem} is the remaining service life at the end of the analysis horizon. The residual value was treated as a negative cost and discounted to present value using the same discount rate applied to all future cash flows [Kneifel and Webb, 2020].

Sensitivity analysis

The sensitivity index was calculated following the general approach for normalized

Table 2. Main economic inputs and LCCA parameters

Parameter	Value	Source
Electricity tariff	0.24 €/kWh without VAT	Public tariff 2025 https://www.energo-pro.bg/
Potable water tariff	1.72 €/m³	Gabrovo Water Operator https://www.vik-gabrovo.com/tzeni
Discount rates	0%, 4%, 8%	Assumed
TER intervals	10, 15, 20 years	Engineering assumption
Drainage of rainwater	0 €/m³	Gabrovo Water Operator https://www.vik-gabrovo.com/tzeni

sensitivity metrics, where the variation in LCC outcomes under parametric changes is expressed relative to the base-case value [Arriola et al., 2009]. To evaluate the robustness of the results, a normalized sensitivity index was applied:

$$SI = \frac{PV_{\text{max}} - PV_{\text{min}}}{PV_{\text{base}}} \quad (3)$$

where: PV_{max} and PV_{min} represent the extreme PV values obtained from the parameter variations, and PV_{base} corresponds to the reference scenario.

RESULTS

Rainwater harvesting potential analysis

A comparison between the potential rainwater runoff collected from the roofs of the Library and the Drama Theater and the average monthly water volumes, required for irrigation, is shown in Figure 4. Since both buildings have sloped roofs with waterproof coatings, a yield coefficient of 0.9 was accepted.

The figure shows that rainwater is not sufficient to provide the entire amount needed for irrigation. In real terms, in May it will be possible to transfer additional rainwater collected in April, as the reservoirs will be gradually filled with water from rain events before the start of the actual irrigation season, but this has a minimal effect on the overall assessment. The percentage ratio of the two parameters from Figure 4 is shown in Figure 5.

In Figure 5, the months in which at least 90% of the required water for irrigation is provided by collected rainwater are shown in green, and the months in which rainwater is insufficient for irrigation and must be supplemented from another water source are shown in orange. It can be seen that in only one of the seven irrigation months the total necessary water can be provided from RWH, when there is more precipitation and water consumption for irrigation has not yet reached its peak (Figure 4A). However, after equalizing the water quantities and preserving the rainwater volume for irrigation in the following months, then two of the months – May and June, can supply more than 90% of the water needed for irrigation from RWH. With this equalization, the need for conventional water sources (such as drinking water supply) is further reduced by additional 10% (from 18% to 8%) in June (Figure 3B).

The blue line in Figure 4B represents the percentage of the total amount of rainwater provided in relation to the total amount of water required for all months. Less than a third of the total water needed for the whole season could potentially be acquired from collected rainwater. For that reason, RWH and use is not considered as a standalone option, but in combination with other water sources that supplement the required volume when necessary.

Proposed alternative options

The potential options are presented in the next sub-sections and they include RWH and

A. B.

Figure 3. Photos of the two buildings with their external downspouts – A. Library and B. Drama Theater

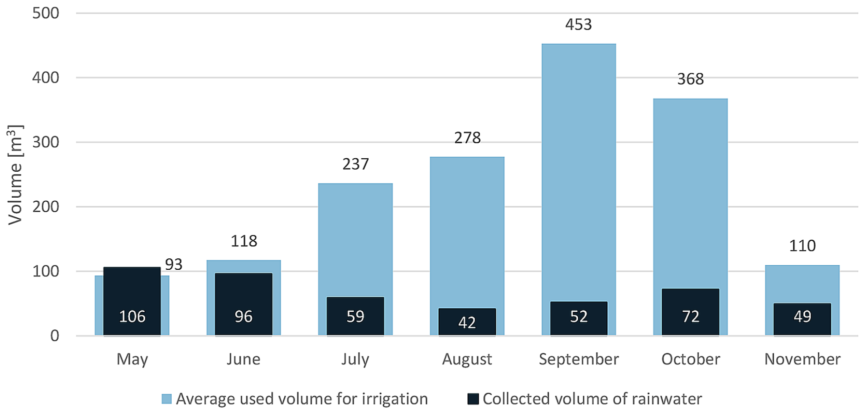

Figure 4. Collected rainwater and average water volume used for irrigation for both areas

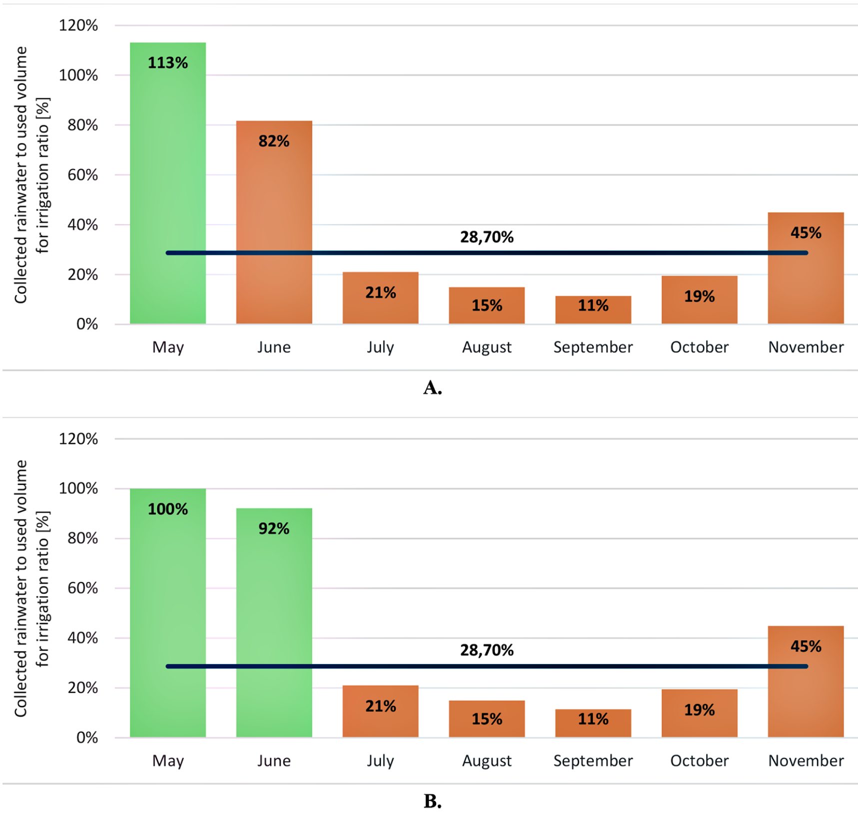

Figure 5. Percentage of irrigation needs covered by rainwater – A. by months, without equalization, and B. – by months with the equalization

use, supplemented with water from: 1) the public water supply network (drinking water); 2) a newly designed drainage well for water intake from surface waters from the bed of the Sinkevitsa River; and 3) a newly designed water supply pipeline from the nearest trunk-main connection point of the existing non-operational Sinkevitsa Dam industrial water supply pipeline.

Option 1 (Sc 1 – RW+N) – Rainwater harvesting from the Central Library and the Drama Theatre buildings with additional water supply from the public network

An engineering drawing of Option 1 is presented in Figure 6. In this option, rainwater is collected in a system of hydraulically connected tanks located in the existing and decommissioned public restroom (New PS 2 in Figure 4) next to

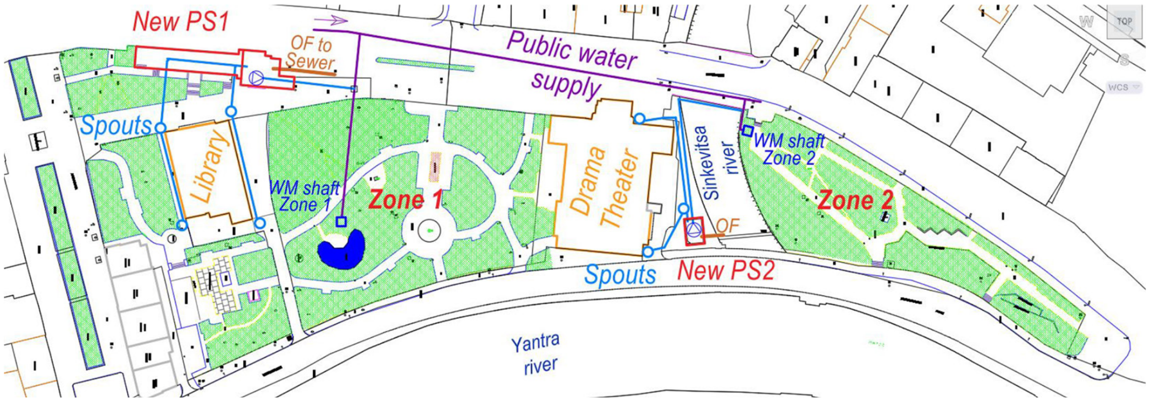

Figure 6. Engineering drawing of Option 1 (Sc 1 – RW+N). Abbreviations: OF – overflow; S – pumping station; WM – water meter

the Drama Theater and another set of tanks in the decommissioned "Ossuary" (New PS 1 in Figure 6), next to the Library. When there is insufficient rainwater, additional water is supplied as before – directly from the public water supply network.

Both buildings with the storage tanks will be equipped with pumps in order to provide the necessary head for the existing irrigation system. During periods when the tanks are empty, water for irrigation will be supplied from the existing connections to the public water supply which does not require any additional pumping. The costs from the LCCA analysis for this option include both capital expenditures (CAPEX) and operational expenditures (OPEX) and cover the costs of construction, installation and commissioning works (including the reconstruction of the existing buildings), technological equipment (delivery and installation of RWH systems with pipes and filters, pumps, tanks, plumbing fittings, and power supply), electrical energy use, and expenditures for drinking water use to the Water Operator of Gabrovo.

Option 2 (Sc 2 – RW+W) – rainwater harvesting from the Central Library and the Drama Theatre buildings with additional water supply from a drainage well in the local Sinkevitsa riverbed

The option uses the same roofs for RWH and the same locations for the storage tanks as the previous option. The difference is that when the rainwater is not enough for a full irrigation cycle, the additional water will be supplied from a newly designed drainage well that is located in Zone 2 and allocates water from the Sinkevitsa riverbed.

Currently the river discharge adjacent to the irrigation zones is $Q_{1\%} = 132.945$ m^3/s (return period of 100 years) and $Q_{0.1\%} = 254.971$ m^3/s (return period of 1000 years) according to the documentation from the Ministry of Environment and Water, Bulgaria from May 2024 [MOEW, 2024]. The level of the riverbed is approximately 5 m below the ground level of the two irrigation zones. An engineering drawing of Option 2 is presented in Figure 7.

The well will be connected to a drainage pipe that will run under the corrected riverbed. The diameter of the pipe is 200 mm, and it will be constructed under drainage layers (gravel and sand) in order to achieve proper primary treatment through infiltration and thus to produce water with lower turbidity before it enters the irrigation system. This is required in order to avoid clogging without the need for additional water treatment steps that will further increase the expenses of the proposed option. A pump will be placed at the bottom of the well which will elevate the water to the storage tanks in the new PS 2. From there, the mixed river water and harvested rainwater will both be pumped to the irrigation system. An engineering drawing of Option 2 is presented in Figure 7.

The cost analysis for Option 2 is based on capital expenditures and technological equipment costs that cover the construction, installation and commissioning works for the RWH system, the pipelines, the drainage well (including the perforated pipe with the filtration layers in the riverbed), the delivery and installation of tanks, pumps, plumbing fittings, power supply networks, and reconstruction of the existing buildings. The operational expenditures cover the electrical energy use and the maintenance of the equipment.

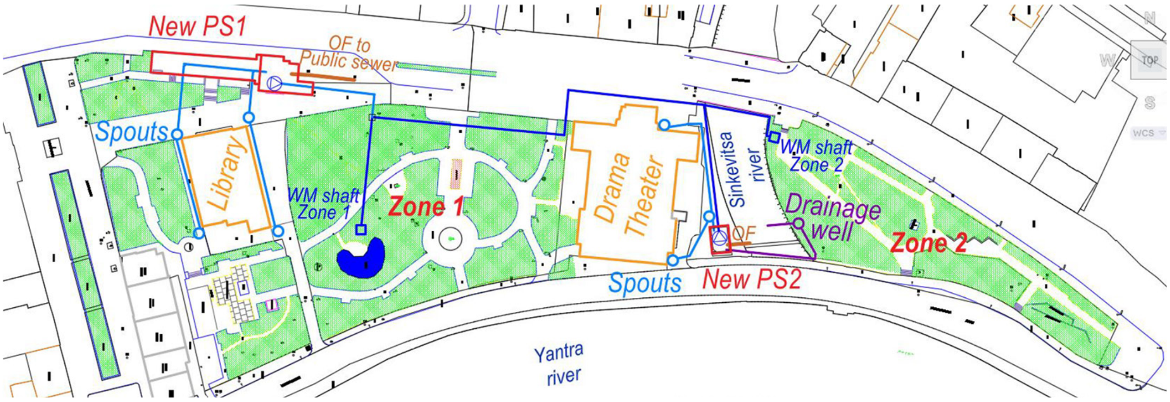

Figure 7. Engineering drawing of Option 2 (Sc 2 – RW+W)

Major advantage of this option, that is apart from the PV analysis, is that the system becomes independent from the Water Operator of Gabrovo and drinking water can be saved instead of being used for irrigation purposes. Thus, this option further decreases the risk of local droughts.

Option 3 (Sc 3 – RW+D) – rainwater harvesting from the Central Library and the Drama Theatre buildings with additional water supply from the local Sinkevitsa dam

Option 3 is also focused on RWH from the same roofs and the same locations for the equalization tanks as the previous option. However, in this option, a newly designed water supply pipeline with an approximate length of 850 m from the decomissioned Kartalov factory distribution shaft (an extension of the existing steel one from the Sinkevitsa dam to the factory), whenever the rainwater is insufficient for proper irrigation. This is the shortest possible route for the pipeline due to the tightly packed underground infrastructure in the Gabrovo city center area. An engineering drawing of Option 3 is presented in Figure 8.

The existing irrigation fields are at an altitude of 390 m above sea level, which implies a natural

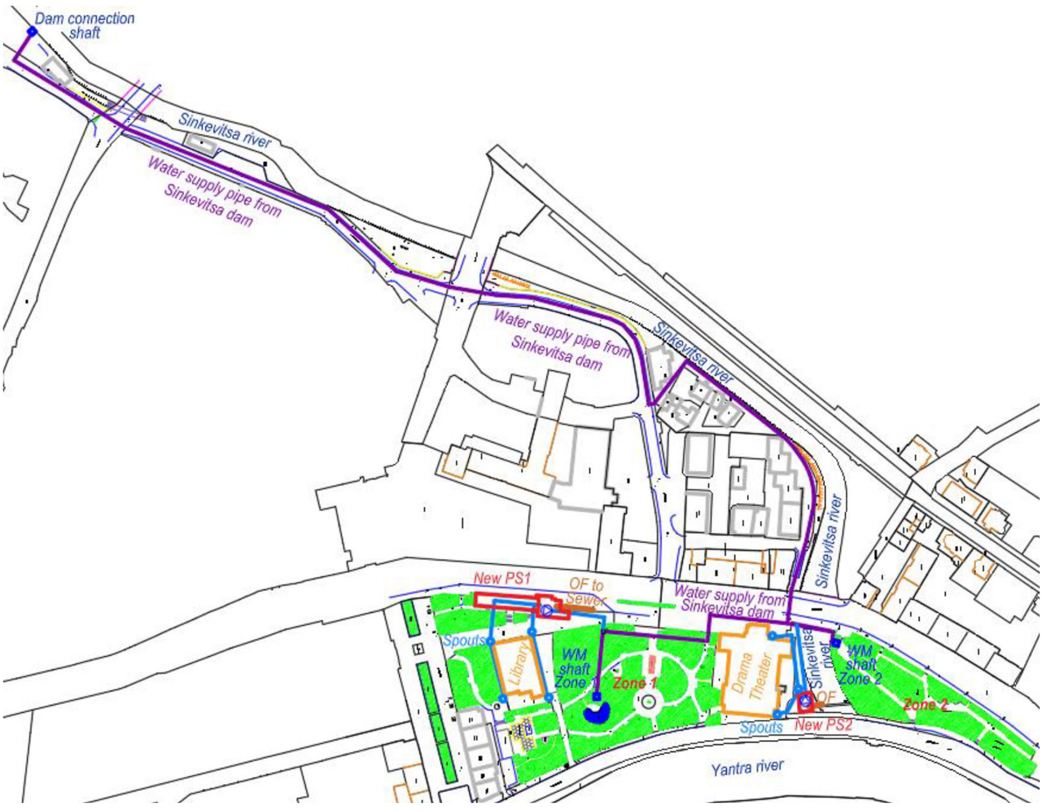

Figure 8. Engineering drawing of Option 3 (Sc 3 – RW+D)

elevation difference of 31–34 m, depending on the water level in the Sinkevitsa dam. This initial head is enough to cover the pressure requirements of the irrigation system without the need for an additional booster pumping. Also, Sinkevitsa dam is a large reservoir with a maximum storage capacity of 500 000 m^3 that is currently unused by other water consumers, meaning that there is no need for additional equalization tanks before the water can enter the irrigation system.

The parameters of the dam are presented in Table 3. The PV cost analysis for Option 3 covers the construction, installation and commissioning works for the RWH system, the pipelines, all of the accompanying facilities (water meter shaft with filter, filtering systems, etc.), the delivery and installation of tanks and pumps for the RWH, plumbing fittings, power supply networks, and reconstruction of the existing buildings. The operational expenditures cover the electrical energy use and the maintenance of the equipment.

Options analysis

Valuation of the options

The input parameters (CAPEX and OPEX) used for the LCCA of the three design options are summarized in Table 4. Capital and operational expenditures for each optionle 4. These values serve as the basis for calculating the discounted life-cycle costs over the selected analysis horizons and discount rates.

Option LCCA comparison

The bar charts of the PV for all alternatives are presented in Figure 9. The evaluation was performed under a 30-year (A) and a 50-year horizon (B). In each graph, the three options are shown for the three technological equipment replacement periods (10, 15, and 20 years). The PV is plotted at three discount rates (0%, 4%, 8%) for every pair of options and TER combination, using separate bars. The layout allows direct visual comparison of how discounting, horizon length, and replacement timing shape lifecycle costs across the alternative irrigation water supply strategies.

Table 3. Parameters of Sinkevitsa dam (data source: Gabrovo Municipality)

Maximum storage capacity	500 000 m^3
Maximum dam wall height	11.80 m
Dam crest elevation	426.80 m
Highest water level elevation (Q1%)	425.70 m
Dead volume elevation	421.50 m
Dam bottom elevation	419.50 m
Crest length	250 m

The two graphs in Figure 9 indicate a clear economic ordering. At typical discount rates (4%), Option 2 – rainwater harvesting with additional supply from a drainage well from the riverbed, delivers the lowest PVs across replacement periods in both horizons. At a high rate (8%), Option 1 – rainwater plus public network top-up, becomes the most favorable option as heavier discounting erodes the value of Option 2's future operating savings. Option 3 – rainwater plus the decommissioned dam line – is consistently the most expensive, particularly with shorter replacement cycles and over 50-year return period. Extending the horizon from 30 to 50 years raises PV for all options, while lengthening the replacement period from 10 to 15–20 years lowers PV with diminishing returns beyond 15 years. The implied crossover between Sc 1 and Sc 2 lies around 5–7%.

From a technical and operational perspective, Option 1 is the simplest to implement because it relies on existing potable infrastructure and requires only standard rainwater storage for irrigation. Option 2 introduces a moderate level of complexity – an intake with a drainage well, short pumping lifts, and basic construction specifics, but it remains within conventional practice and is readily managed with storage and screening. Option 3 is the most demanding, since the long, decommissioned transmission asset needs rehabilitation, uncertain rights (Gabrovo municipality has to acquire the pipeline completely), and construction access can drive schedule and cost risk.

Ecologically and in terms of drought resilience, all options reduce potable water demand by substituting harvested rainwater. Option 2 provides the strongest portfolio diversification with a relatively low energy footprint if abstraction respects environmental flows and intake design standards. Option 1 also has a relatively low local ecological footprint because it avoids new abstraction, but it delivers the least reduction in potable water reliance. Option 3 can add storage-backed robustness if the dam allocation is secure, yet its longer conveyance and significant construction footprint make its environmental performance weaker.

Table 4. Capital and operational expenditures for each option

Capital expenditures (CAPEX)		Sc 1-RW+N	Sc 2-RW+W	Sc 3-RW+D
Construction and installation works	EUR	61 161.90	97 975.50	209 040.87
Technological equipment	EUR	6 237.76	8 189.87	6 237.76
Total Capital expenditures	EUR	67 399.66	10 6165.37	21 5278.63
Operational expenditures (OPEX)				
Annual potable water use costs	EUR	2 288.91	-	-
Annual electricity costs	EUR	24.54	183.45	24.54
Total Operational expenditures	EUR	2 313.45	183.45	24.54

Figure 9. PV comparison of the proposed options: A. – 30-year return period and B. – 50-year return period

Overall, Option 2, is the preferred option, since it is the least costly at realistic discount rates, technically tractable, and environmentally balanced. If financing costs are unusually high or river-abstraction permits are delayed, Option 1 is a pragmatic alternative despite smaller reductions in potable use. Also, Option 1 can be executed as a temporary solution until Option 2 is fully built if any unpredicted issues with the construction of the drainage well abstraction occur. Option 3 is considered not economically competitive and should not be pursued due to its higher costs and impacts.

To evaluate the relative influence of the key economic parameters on the life-cycle cost outcomes, a sensitivity index was calculated for each option. The analysis was performed by varying one parameter at a time while keeping the remaining parameters fixed at representative baseline values. Specifically, the discount-rate sensitivity was evaluated for the 30-year horizon with a TER of 15 years. The TER sensitivity was assessed for the 30-year horizon at a discount rate of 4%, and the horizon sensitivity was computed at a 4% discount rate with TER set to 15 years.

These standardized conditions allow the three options to be compared on a common basis and prevent the generation of multiple overlapping diagrams. The resulting sensitivity indices for discount rate (DR), TER and analysis horizon were plotted in a single radar chart to provide a clear and integrated overview of how strongly each option responds to changes in the underlying economic assumptions (Figure 9).

Figure 10 confirms that Option RW+D is the most sensitive to changes in the discount rate, reflecting its high upfront capital intensity. Option RW+N is predominantly influenced by the analysis horizon due to cumulative potable water use costs. Option RW+W exhibits the most balanced sensitivity profile. Across all options, the sensitivity to TER is minimal, indicating that replacement timing plays a comparatively minor role in long-term economic performance.

DISCUSSION

Option 1 – RW+N requires the lowest upfront investment, as it builds on the existing potable water supply infrastructure and adds only the storage capacity necessary for harvesting rooftop rainwater. However, its contribution to reducing potable water consumption is limited, since the system continues to rely predominantly on drinking water to meet irrigation demand. As a result, annual operating costs remain strongly influenced by potable water use, while electricity consumption is negligible due to the relatively small pumping requirements associated with rainwater collection alone. The need for two separate storage facilities, however, represents a notable capital component, and these tanks form the structural foundation for Option RW+W. In the latter configuration, the same storage infrastructure is utilised more efficiently by supplementing rooftop runoff with additional abstraction from the Sinkevitsa riverbed, thereby expanding the usable non-potable water volume and improving the overall effectiveness of the system.

At a 4% discount rate, Option RW+N and RW+W exhibit nearly identical PV costs for both horizons. This convergence is primarily driven by the relatively low price of potable water in the study area, which limits the economic penalty of continued reliance on the public water supply in RW+N. In addition, the absence of any stormwater discharge fee, which is practice in some countries [Nickel et al., 2014; Tasca et al., 2018; Tasca et al., 2019], further reduces the operational cost advantage of RW+W. As a result, the financial difference between relying partly on potable

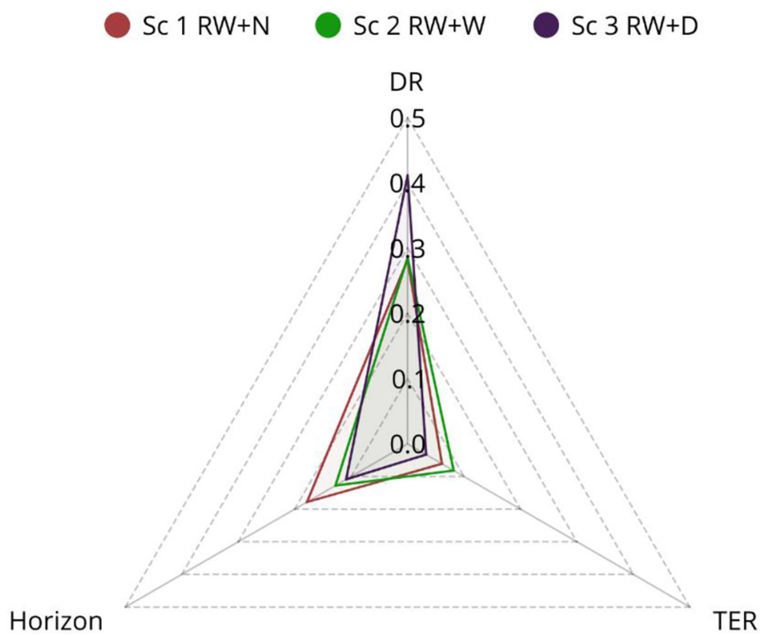

Figure 10. Sensitivity indices of the three options for discount rate, analysis horizon and TER

water (RW+N) and fully substituting it with non-potable sources (RW+W) becomes small when discounted at a moderate rate such as 4%.

Option RW+W entails higher initial investment compared to RW+N, primarily due to the construction of the drainage well, the subsurface intake pipe and the associated pumping equipment. These additions enable the abstraction of surface water from the Sinkevitsa riverbed to provide necessary water volumes in dry weather. As a result, the system eliminates the need for potable water in all months of the irrigation season, thereby substantially reducing annual operating costs. However, the inclusion of additional mechanical components also increases the long-term maintenance burden, as periodic inspection, cleaning and replacement of pumps, filters and drainage elements become necessary. In this sense, RW+W trades higher upfront and maintenance expenditures for a complete transition away from drinking water and a more resilient and autonomous irrigation supply.

Option RW+D requires the highest initial investment of all alternatives, mainly due to the construction of a new transmission pipeline from the Sinkevitsa dam and the rehabilitation or replacement of existing non-operational infrastructure. Once built, however, this configuration relies on gravity-fed supply from the dam, which virtually eliminates operational expenditures during the service life of the system. Similar to RW+W, it completely removes the need for potable water for irrigation, but unlike RW+W, it achieves this with minimal long-term energy use and maintenance, as no continuous pumping from a shallow intake or drainage system is required.

Financial aspect

Figure 9 reveals strong interactions among the technological equipment replacement interval (TER), the discount rate, and the analysis horizon. Similar interdependencies and their implications for cost-based decision-making have been highlighted in recent LCCA research. For instance, Lee et al. show that assumed service lives and discount rates are inseparable in LCCA of water supply pipelines and directly affect rehabilitation timing and budget profiles [Lee et al., 2017]. Furthermore, Ghobadi et al. demonstrate that even when per-asset LCC is fixed, the choice of planning horizon and replacement timing interact to change system-level costs [Ghobadi et al., 2021].

TER × discount rate

At low discount rates (0–4%), shorter TER intervals substantially increase the PV of all options, as replacement cycles remain largely undiscounted. This effect diminishes at higher discount rates (8%), where future replacement events are heavily discounted and thus contribute minimally to PV. These findings are consistent with limitations of LCCA, because high discount rates suppress the influence of long-term capital renewal [Mearig and Morris, 2024]. Under such conditions, Option 1 – RW+N, which carries the largest annual operating expenditures, becomes comparatively more favourable because its long-term OPEX is rapidly discounted. This major influence of the discount rate has been described in various studies, where capital-intensive alternatives are disproportionately penalised by discounting [Wu et al., 2010; Nordman et al., 2018; Ilyas et al., 2021].

TER × analysis horizon

The importance of TER increases with the length of the analysis horizon. Over a 50-year period, multiple replacement cycles occur, producing a cumulative impact particularly visible for Options RW+W and RW+D. Conversely, for Option RW+N, the effect of TER is overshadowed by the accumulation of operating expenditure over long horizons. Similar horizon-related effects have been documented in building and water-infrastructure LCCAs, where long service lives amplify maintenance and renewal costs [Wallingford et al., 2004; Ira et al., 2017].

Analysis horizon × discount rate

At low discount rates, extending the analysis horizon from 30 to 50 years significantly increases the PV of RW+N due to the prolonged accumulation of potable water use costs. However, at high discount rates, the difference between 30- and 50-year horizons is minimal across all options, as future expenditures carry little present-value weight. This inversion effect – where OPEX-intensive alternatives appear more favourable under high discount rates - has been identified in several studies as a methodological limitation of LCCA when long-term operating costs interact with aggressive discounting [Zhao et al., 2022; Safarpour et al., 2022].

Risk and operational responsibility

From an operational risk perspective, Option RW+N places the least burden on the Municipality, as the primary source of irrigation water remains the existing potable water network, whose operation and reliability are ensured by the regional water utility. Under this configuration, the Municipality is responsible only for the rainwater harvesting components, while the core water supply risk is effectively externalized. In contrast, both RW+W and RW+D require the Municipality to assume full responsibility for the performance, maintenance and reliability of the entire non-potable water supply infrastructure. This shift includes operational oversight of pumps, filters, storage systems, drainage wells or intake structures, as well as the transmission pipeline in the case of RW+D. As a result, RW+N represents the lowest-risk option from an asset-management standpoint, whereas RW+W and RW+D entail a substantially higher operational and institutional commitment.

An additional source of uncertainty in Option RW+D is the condition of the existing steel transmission pipeline from the former industrial system. As the pipeline is currently non-operational and its structural integrity has not been verified, there is a significant risk that parts of the asset may require rehabilitation or full replacement. Such unforeseen works could substantially increase the actual capital cost of the option and introduce construction delays. This uncertainty further elevates the implementation risk of RW+D compared to RW+N and RW+W, where the extent and condition of the required infrastructure are better known.

Water supply reliability

With respect to water supply reliability, all three options provide sufficient irrigation water during normal hydrological years. Options RW+W and RW+D rely on the Sinkevitsa reservoir, which is maintained at full storage for most of the year and is only partially released in advance of forecasted high-intensity rainfall events. The available storage volume in the reservoir exceeds the combined irrigation demand of the two zones by a substantial margin, ensuring a high degree of operational security.

CONCLUSIONS

The study identified a technically feasible and economically defensible strategy to reduce (and, where possible, eliminate) potable-water use for urban park irrigation under the site-specific constraints of the two Gabrovo central area parks. The results clearly show that RWH is not sufficient as a standalone supply for seasonal irrigation: even with storage, it reliably covers less than one-third of the demand, meaning that a supplementary non-potable source is necessary for complete or partial drinking-water substitution.

The main contribution of the paper is the quantified, long-horizon, cost-robust ranking of three hybrid RWH configurations under a discounted LCCA framework that explicitly tests how conclusions shift with DR, analysis horizon, and TER. At a reference DR of 4%, the hybrid option coupling RWH with a drainage-well intake (RW+W) delivers the lowest present-value cost while fully substituting potable water and remains the most advantageous choice across most tested conditions. In contrast, RW+N only appears economically competitive under conditions that heavily discount future operating costs (high DR), because its continued reliance on potable supply translates into persistent OPEX. RW+D is consistently economically dominated due to high upfront cost and additional uncertainty associated with rehabilitating the transmission pipeline.

By demonstrating strong and predictable interactions between DR, horizon length, and TER, the study fills a practical gap in the planning literature: municipalities often compare alternatives using single-point assumptions, whereas this analysis shows when and why the preferred option can (or cannot) change - e.g., short TERs become disproportionately costly at low DRs (weak discounting of multiple renewals), while OPEX-heavy solutions become relatively more attractive as DR increases. This provides decision-makers with actionable design guidance, not just a single "best" option. For the case study, RW+W with a 15–20-year replacement interval emerges as the most credible long-term solution when economic performance, potable-water savings, technical complexity, and implementation risk are considered together.

These findings open clear prospects for wider application: the framework can be used by other municipalities to screen hybrid irrigation supply portfolios, stress-test conclusions against financial and asset-management assumptions, and prioritize investments that maximize potable-water savings under climate variability. Future extensions could integrate water-quality and treatment requirements, rainwater sewerage discharge taxing, climate-driven demand and rainfall projections, and operational reliability data (e.g., well yield variability) to further strengthen implementation readiness and transferability.

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